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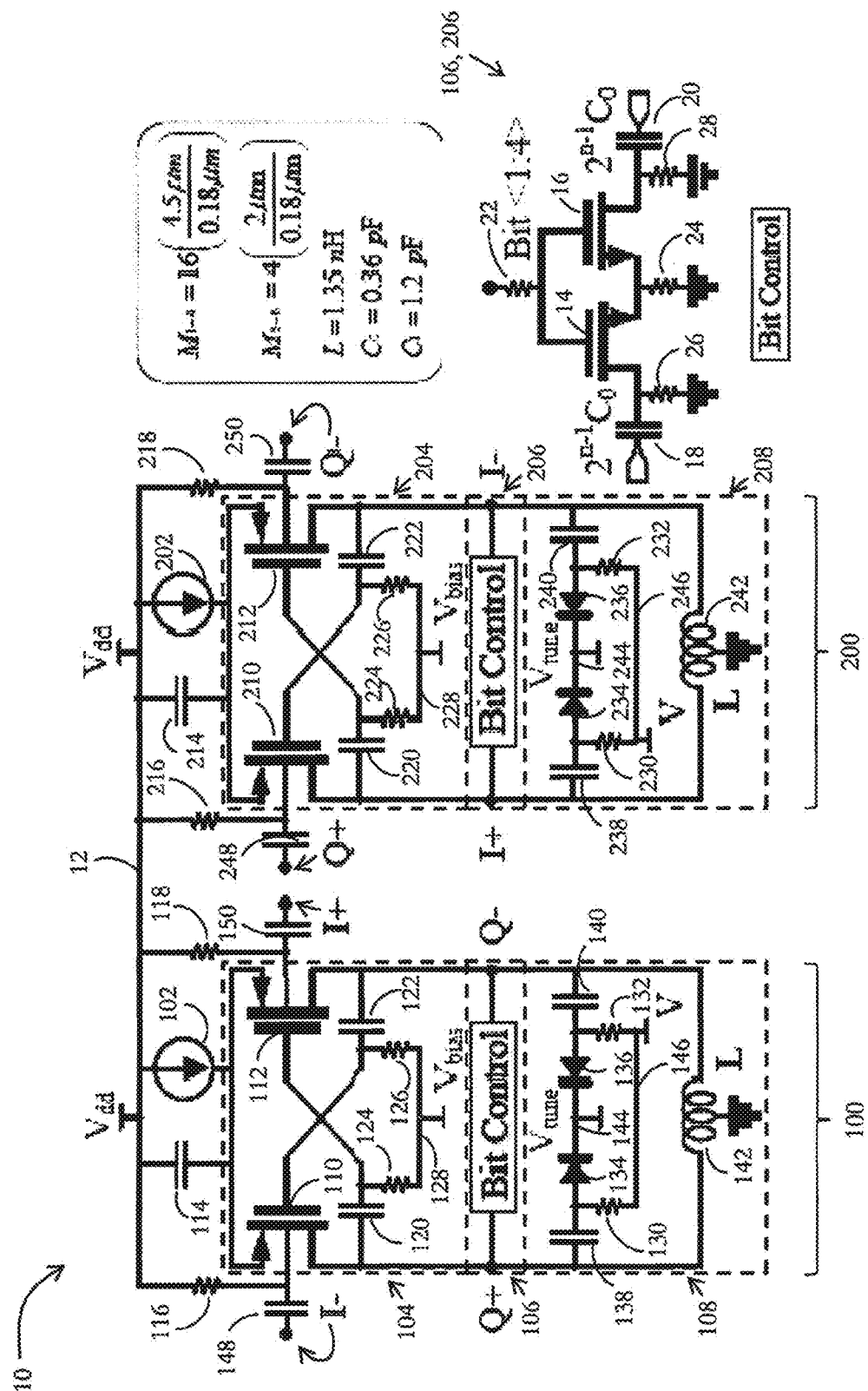


Figure 1

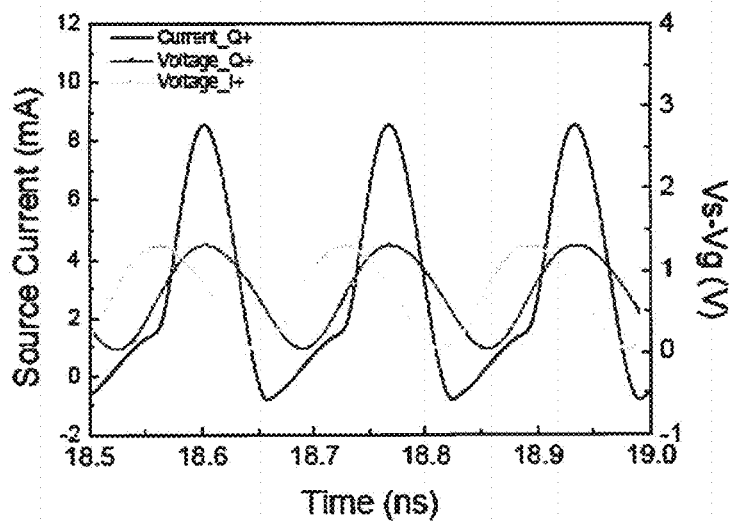


Figure 2A

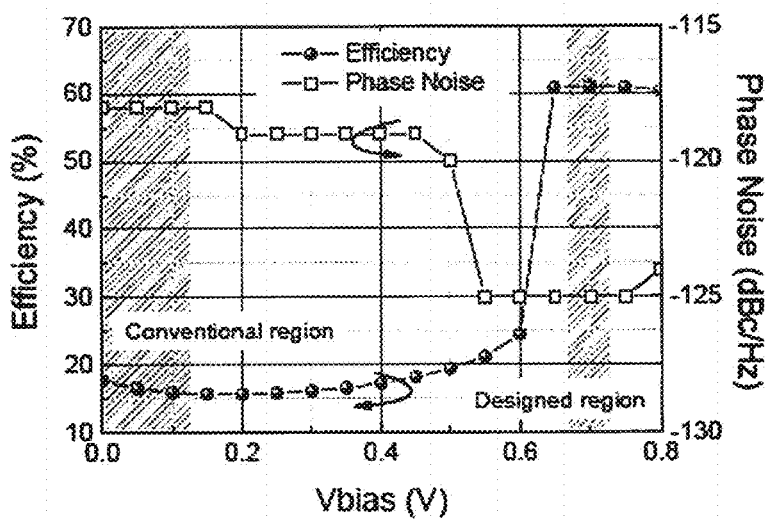


Figure 2B

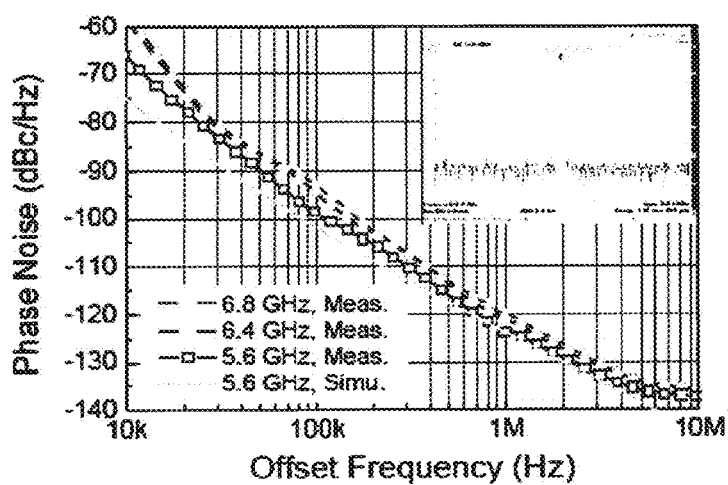


Figure 3A

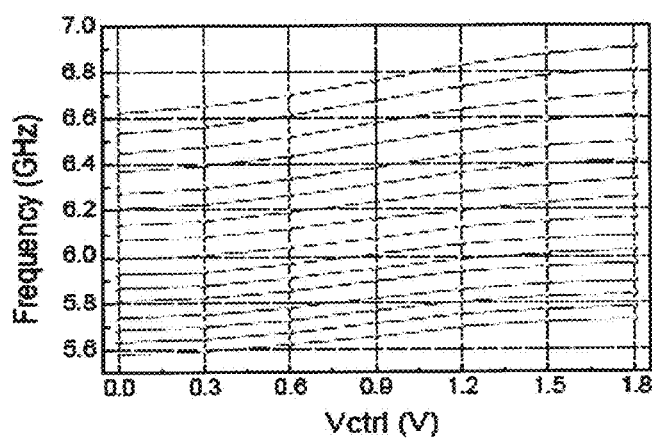


Figure 3B

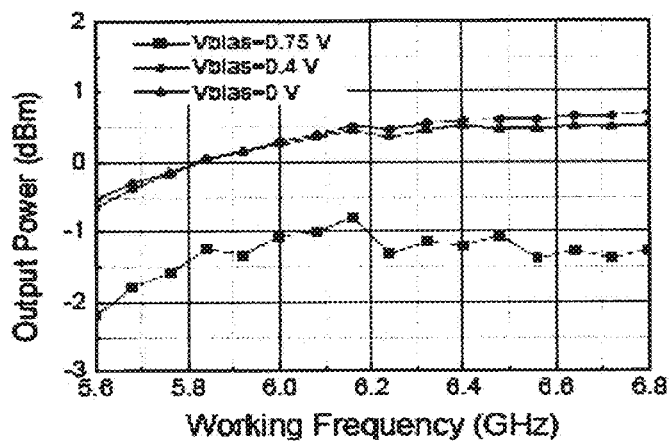


Figure 3C

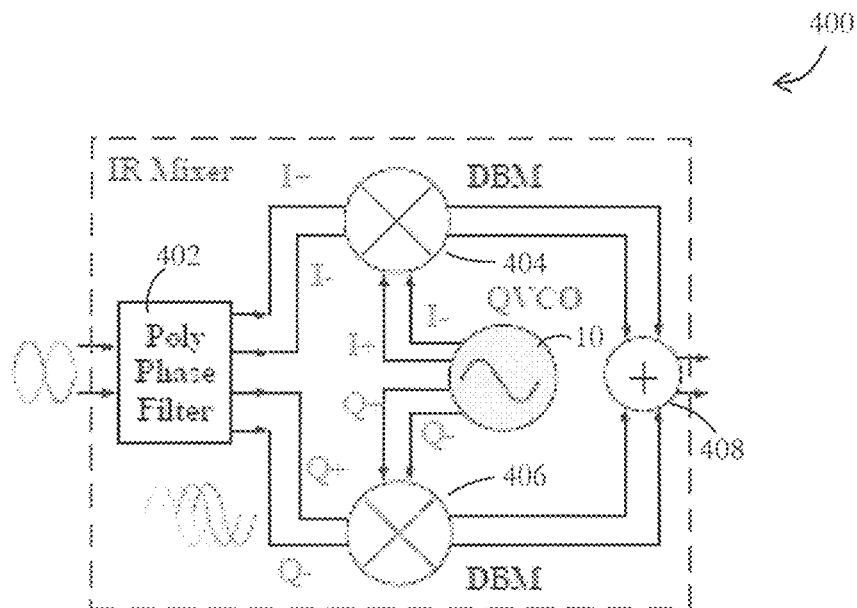


Figure 4A

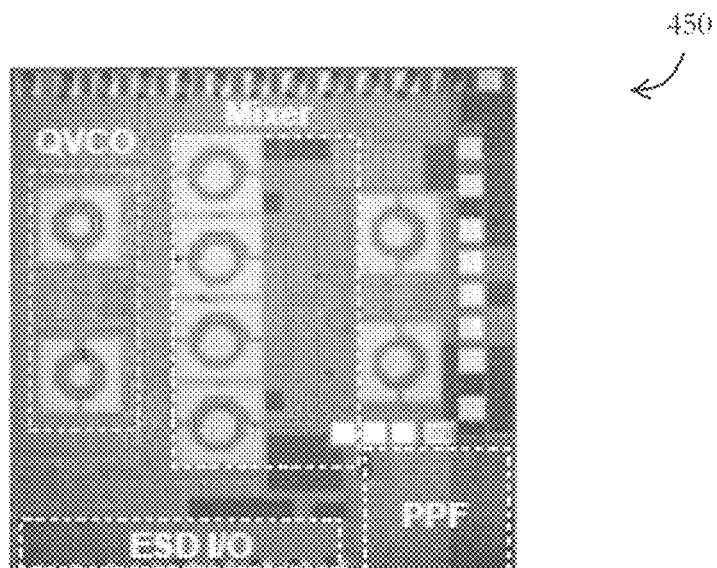


Figure 4B

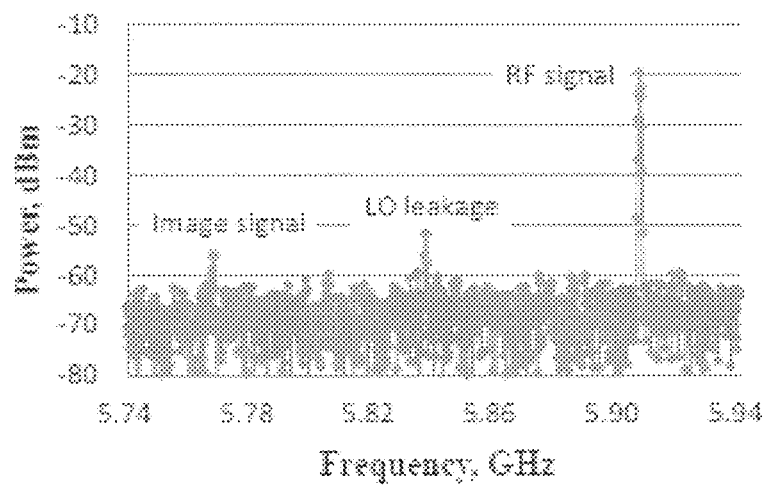


Figure 4C

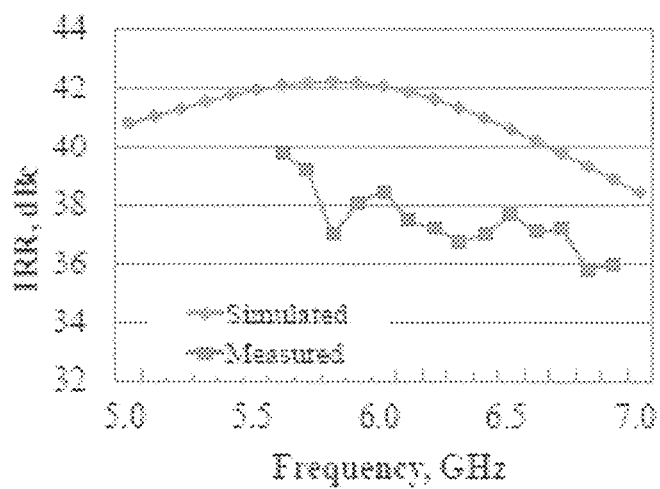


Figure 4D

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# QUADRATURE VOLTAGE CONTROLLED OSCILLATOR

## TECHNICAL FIELD

The present invention relates to a quadrature voltage controlled oscillator and particularly, although not exclusively, to a CMOS wideband low phase noise Class-C quadrature voltage controlled oscillator.

## BACKGROUND OF THE INVENTION

Quadrature voltage controlled oscillator plays an important role in modern wireless communication systems, and it is particularly useful in applications that require high fidelity quadrature signals, such as in wireless and wired transceivers. One of the most popular type of quadrature voltage controlled oscillator is LC quadrature voltage controlled oscillator, and it comprises two symmetric LC tanks voltage controlled oscillators coupled with each other. Typically, LC quadrature voltage controlled oscillator can be classified into parallel-coupled quadrature voltage controlled oscillator (P-QVCO) and series-coupled quadrature voltage controlled oscillator (S-QVCO). For P-QVCO, the coupling transistors are arranged in parallel with the switching pairs, whereas for S-QVCO, the transistors are stacked for series coupling.

In general, P-QVCO and S-QVCO can provide good phase noise performance and have relative low power consumption. However, they suffer from various problems. For example, the coupling transistors in both P-QVCO and S-QVCO may introduce additional noise, and as a result the phase noise of the quadrature voltage controlled oscillator may be degraded. Also, the oscillation efficiency in conventional P-QVCO and S-QVCO is generally low.

Accordingly, there exists a need to provide a quadrature voltage controlled oscillator that is more efficient in operation, compact in design, and more importantly, less prone to the above problems.

## SUMMARY OF THE INVENTION

In accordance with a first aspect of the present invention, there is provided a quadrature voltage controlled oscillator, comprising: a first voltage controlled oscillator having a first current source, a first oscillator circuit, a first tuning circuit, and a first resonator tank electrically connected with each other; a second voltage controlled oscillator having a second current source, a second oscillator circuit, a second tuning circuit, and a second resonator tank electrically connected with each other; the first oscillator circuit comprises a first transistor, a second transistor and a first biasing circuit connected between the first and second transistors for biasing the first and second transistors to operate in Class-C mode; the second oscillator circuit comprises a third transistor, a fourth transistor and a second biasing circuit connected between the third and fourth transistors for biasing the third and fourth transistors to operate in Class-C mode; wherein bulk terminals of the first and second transistors are coupled with drain terminals of the third and fourth transistors respectively, and bulk terminals of the third and fourth transistors are coupled with drain terminals of the first and second transistors respectively, such that the first voltage controlled oscillator is electrically coupled with the second voltage controlled oscillator.

In one embodiment of the first aspect, the first, second, third and fourth transistors are PMOS transistors.

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In one embodiment of the first aspect, the first biasing circuit comprises a low pass RC circuit arranged to provide a bias voltage to the first and second transistors to bias the first and second transistors to operate in Class-C mode.

5 In one embodiment of the first aspect, the second biasing circuit comprises a low pass RC circuit arranged to provide a bias voltage to the third and fourth transistors to bias the third and fourth transistors to operate in Class-C mode.

10 In one embodiment of the first aspect, source terminals of the first and second transistors are connected with each other; and source terminals of the third and fourth transistors are connected with each other.

In one embodiment of the first aspect, a gate terminal of the first transistor is connected with a drain terminal of the second transistor through the first biasing circuit, and a gate terminal of the second transistor is connected with a drain terminal of the first transistor through the first biasing circuit.

20 In one embodiment of the first aspect, a gate terminal of the third transistor is connected with a drain terminal of the fourth transistor through the second biasing circuit, and a gate terminal of the fourth transistor is connected with a drain terminal of the third transistor through the second biasing circuit.

25 In one embodiment of the first aspect, the bulk terminal of the first transistor is connected with a drain terminal of the fourth transistor, the bulk terminal of the second transistor is connected with a drain terminal of the third transistor, the bulk terminal of the third transistor is connected with a drain terminal of the first transistor, and the bulk terminal of the fourth transistor is connected with a drain terminal of the second transistor.

30 In one embodiment of the first aspect, the first current source is connected between a node and the source terminals of the first and second transistors for supplying current to the first and second transistors.

35 In one embodiment of the first aspect, the quadrature voltage controlled oscillator further comprises a first capacitor connected in parallel with the first current source between the node and the source terminals of the first and second transistors.

40 In one embodiment of the first aspect, the second current source is connected between a node and the source terminals of the third and fourth transistors for supplying current to the third and fourth transistors.

45 In one embodiment of the first aspect, the quadrature voltage controlled oscillator further comprises a second capacitor connected in parallel with the second current source between the node and the source terminals of the third and fourth transistors.

50 In one embodiment of the first aspect, the first and second current sources are the same current source.

In one embodiment of the first aspect, the first tuning circuit comprises a capacitor array.

55 In one embodiment of the first aspect, the first tuning circuit is a 4-bit switchable capacitor array.

In one embodiment of the first aspect, the second tuning circuit comprises a capacitor array.

60 In one embodiment of the first aspect, the second tuning circuit is a 4-bit switchable capacitor array.

In one embodiment of the first aspect, the first resonator tank comprises an LC resonator circuit.

In one embodiment of the first aspect, the second resonator tank comprises an LC resonator circuit.

65 In one embodiment of the first aspect, the first tuning circuit and the first resonator tank are connected across the drain terminals of the first and second transistors.



In one embodiment of the first aspect, the second tuning circuit and the second resonator tank are connected across the drain terminals of the third and fourth transistors.

In one embodiment of the first aspect, the first voltage controlled oscillator is substantially identical to the second voltage controlled oscillator.

In one embodiment of the first aspect, the quadrature voltage controlled oscillator is a CMOS quadrature voltage controlled oscillator.

In accordance with a second aspect of the present invention, there is provided a radiofrequency transceiver comprising the quadrature voltage controlled oscillator in accordance with the first aspect.

It is an object of the present invention to address the above needs, to overcome or substantially ameliorate the above disadvantages or, more generally, to provide an improved quadrature voltage controlled oscillator.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the present invention will now be described, by way of example, with reference to the accompanying drawings in which:

FIG. 1 is a circuit diagram showing a quadrature voltage controlled oscillator in accordance with one embodiment of the present invention;

FIG. 2A is a graph showing the simulated time-domain source current and source-gate voltage waveforms of the PMOS transistor for the quadrature voltage controlled oscillator of FIG. 1;

FIG. 2B is a graph showing the simulated oscillation efficiency and phase noise against the biasing voltage for the quadrature voltage controlled oscillator of FIG. 1;

FIG. 3A is a graph showing phase noise at different offset frequencies for a quadrature voltage controlled oscillator fabricated based on the circuit diagram of FIG. 1;

FIG. 3B is a graph showing the frequency tuning curves for the quadrature voltage controlled oscillator fabricated based on the circuit diagram of FIG. 1;

FIG. 3C is a graph showing the measured output power at different working frequencies for different bias voltages for the quadrature voltage controlled oscillator fabricated based on the circuit diagram of FIG. 1;

FIG. 4A is a circuit diagram showing an image reject mixer having a quadrature voltage controlled oscillator of FIG. 1 in accordance with one embodiment of the present invention;

FIG. 4B is a chip micrograph showing an image reject mixer fabricated based on the circuit diagram of FIG. 4A in accordance with one embodiment of the present invention;

FIG. 4C is a graph showing the output power spectrum of the image reject mixer of FIG. 4B; and

FIG. 4D is a graph showing the image rejection ratio bandwidth performance of the image reject mixer of FIG. 4B.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring to FIG. 1, there is provided a quadrature voltage controlled oscillator 10, comprising: a first voltage controlled oscillator 100 having a first current source 102, a first oscillator circuit 104, a first tuning circuit 106, and a first resonator tank 108 electrically connected with each other; a second voltage controlled oscillator 200 having a second current source 202, a second oscillator circuit 204, a second tuning circuit 206, and a second resonator tank 208 electri-

cally connected with each other; the first oscillator circuit 104 comprises a first transistor 110, a second transistor 112 and a first biasing circuit connected between the first and second transistors 110, 112 for biasing the first and second transistors 110, 112 to operate in Class-C mode; the second oscillator circuit 204 comprises a third transistor 210, a fourth transistor 212 and a second biasing circuit connected between the third and fourth transistors 210, 212 for biasing the third and fourth transistors 210, 212 to operate in Class-C mode; wherein bulk terminals of the first and second transistors 110, 112 are coupled with drain terminals of the third and fourth transistors 210, 212 respectively, and bulk terminals of the third and fourth transistors 210, 212 are coupled with drain terminals of the first and second transistors 110, 112 respectively, such that the first voltage controlled oscillator 100 is electrically coupled with the second voltage controlled oscillator 200. Preferably, the first, second, third and fourth transistors 110, 112, 210, 212 are all p-channel MOSFET (PMOS transistors). The quadrature voltage controlled oscillator 10 in the present invention is arranged for Class-C operation to generate high and narrow current pulses, and this results in high fundamental current amplitude  $I_{\omega_0}$ .

In the present embodiment, the quadrature voltage controlled oscillator 10 is preferably a wideband low phase noise quadrature voltage controlled oscillator implemented in 0.18  $\mu\text{m}$  complementary metal-oxide-semiconductor (CMOS). In one example, the quadrature voltage controlled oscillator 10 is constructed as a differential voltage controlled oscillator that has reduced flicker noise.

Referring to FIG. 1, the first voltage controlled oscillator 100 includes a current source 102, an oscillator circuit 104, a tuning circuit 106, and a resonator tank 108 electrically connected with each other. In the present embodiment, the current source 102 connected between a node 12 biased at voltage  $V_{dd}$  and the source terminals of the first and second PMOS transistors 110, 112 for supplying current to the source terminals of the first and second PMOS transistors 110, 112. In one embodiment, a capacitor 114 is arranged in parallel with the current source 102 to ensure that the first and second PMOS transistors 110, 112 operate in an active region. Optionally, a resistor 116 is connected between the node 12 and bulk terminal of the first PMOS transistor 110 and another resistor 118 is connected between the node 12 and the bulk terminal of the second PMOS transistor 112. In the present embodiment, the source terminals of the first and second PMOS transistors 110, 112 are directly connected with each other.

The oscillator circuit 104 of the first voltage controlled oscillator 100 includes the first PMOS transistor 110, the second PMOS transistor 112, and the biasing circuit arranged to provide a respective bias voltage to the first and second PMOS transistors 110, 112 for biasing them to operate in Class-C mode. Preferably, the biasing circuit is a low pass RC circuit. As shown in FIG. 1, the RC circuit includes two capacitors 120, 122 and two resistors 124, 126 in electrical connection with each other. Preferably, the resistors 120, 122 are connected to a common node 128 biased at voltage  $V_{bias}$ . In one embodiment, one resistor 126 of the RC circuit is connected between the gate terminal of the first PMOS transistor 110 and the node 128, and another resistor 124 of the RC circuit is connected between the gate terminal of the second PMOS transistor 112 and the node 128. In one embodiment, one capacitor 120 of the RC circuit is connected between the drain terminal of the first PMOS transistor 110 and the gate terminal of the second PMOS transistor 112, and another capacitor 122 of the RC circuit is

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connected between the drain terminal of the second PMOS transistor **112** and the gate terminal of the first PMOS transistor **110**. By providing a biasing circuit arrangement as described above, the first and second PMOS transistors **110**, **112** can be cross-coupled with each other, i.e., with a gate terminal of one being connected with a drain terminal of the other. Preferably, the oscillator circuit **104** has a substantially symmetric circuit architecture.

In the present embodiment, the first voltage controlled oscillator **100** further includes the tuning circuit **106** connected between the first and second PMOS transistors. As shown in FIG. 1, the tuning circuit **106** is connected across the drain terminals of the first and second PMOS transistors **110**, **112**. Preferably, the tuning circuit **106** is a capacitor array circuit, such as a 4-bit switchable capacitor array as illustrated. Referring to FIG. 1, the 4-bit switchable capacitor array **106** includes two n-channel MOSFETs (NMOS transistors) **14**, **16**, two capacitors **18**, **20**, and a number of resistors **22**, **24**, **26**, **28** in electrical connection with each other. Specifically, the gate terminals of the two NMOS transistors **14**, **16** are connected with each other, and with a resistor **22**. The source terminals of the two NMOS transistors **14**, **16** are connected with each other, and with a grounded resistor **24**. The drain terminals of each NMOS transistors **14**, **16** are connected with a grounded resistor **26**, **28** as well as a capacitor **18**, **20**. Preferably, the two capacitors **18**, **20** are electrically connected with the drain terminals of the first and second PMOS transistors **110**, **112** respectively. Preferably, the capacitor array circuit **106** has a substantially symmetric circuit architecture. The capacitor array circuit **106** in the present embodiment provides a wide tuning range.

In one embodiment, the first voltage controlled oscillator **100** further includes the resonator tank **108** in the form of a LC resonator circuit. Preferably, the LC resonator circuit **108** includes two branches arranged in parallel between the drain terminals of the first and second PMOS transistors **110**, **112**. Preferably, the LC resonator includes two resistors **130**, **132**, two diodes **134**, **136**, two capacitors **138**, **140**, and an inductor **142** in electrical connection with each other. As shown in FIG. 1, in the first branch, there are two diodes **134**, **136** connected to the same node **144** biased at  $V_{tune}$ . The diodes **134**, **136** are biased in a manner such that current can only flow into but not out of the node **144**. The first branch further includes two capacitors **138**, **140** each connected between a drain terminal of the respective first and second PMOS transistors **110**, **112** and a respective diode **134**, **136**. A first sub-branch comprising two resistors **130**, **132** is arranged in parallel with the two diodes **134**, **136**. The resistors **130**, **132** in the sub-branch are connected at the same node **146** at voltage  $V$ . In the present example, the voltage  $V$  is 0.7 volt. In the present embodiment, the second branch includes an inductor **142** connected to ground, and in parallel with the first branch. Preferably, the LC resonator circuit **108** has a substantially symmetric circuit architecture.

Referring to FIG. 1, the second voltage controlled oscillator **200** also includes a current source **202**, an oscillator circuit **204**, a tuning circuit **206**, and a resonator tank **208** electrically connected with each other. In the present embodiment, the current source **202** connected between a node **12** biased at voltage  $V_{dd}$  and the source terminals of the third and fourth PMOS transistors **210**, **212** for supplying current to the source terminals of the third and fourth PMOS transistors **210**, **212**. In one embodiment, a capacitor **214** is arranged in parallel with the current source **202** to ensure that the third and fourth PMOS transistors **210**, **212** operate

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in an active region. Optionally, a resistor **216** is connected between the node **12** and bulk terminal of the third PMOS transistor **210** and another resistor **218** is connected between the node **12** and the bulk terminal of the fourth PMOS transistor **212**. In the present embodiment, the source terminals of the third and fourth PMOS transistors **210**, **212** are directly connected with each other.

The oscillator circuit **204** of the second voltage controlled oscillator **200** includes the third PMOS transistor **210**, the fourth PMOS transistor **212**, and the biasing circuit arranged to provide a respective bias voltage to the third and fourth PMOS transistors **210**, **212** for biasing them to operate in Class-C mode. Preferably, the biasing circuit is a low pass RC circuit. As shown in FIG. 1, the RC circuit includes two capacitors **220**, **222** and two resistors **224**, **226** in electrical connection with each other. Preferably, the resistors **224**, **226** are connected to a common node **228** biased at voltage  $V_{bias}$ . In one embodiment, one resistor **226** of the RC circuit is connected between the gate terminal of the third PMOS transistor **210** and the node **228**, and another resistor **224** of the RC circuit is connected between the gate terminal of the fourth PMOS transistor **212** and the node **228**. In one embodiment, one capacitor **220** of the RC circuit is connected between the drain terminal of the third PMOS transistor **210** and the gate terminal of the fourth PMOS transistor **212**, and another capacitor **222** of the RC circuit is connected between the drain terminal of the fourth PMOS transistor **212** and the gate terminal of the third PMOS transistor **210**. By providing a biasing circuit arrangement as described above, the third and fourth PMOS transistors **210**, **212** can be cross-coupled with each other, i.e., with a gate terminal of one being connected with a drain terminal of the other. Preferably, the oscillator circuit **204** has a substantially symmetric circuit architecture.

In the present embodiment, the second voltage controlled oscillator **200** further includes the tuning circuit **206** connected between the third and fourth PMOS transistors **210**, **212**. As shown in FIG. 1, the tuning circuit **206** is connected across the drain terminals of the third and fourth PMOS transistors **210**, **212**. Preferably, the tuning circuit **206** is a capacitor array circuit, such as a 4-bit switchable capacitor array as illustrated. Referring to FIG. 1, the 4-bit switchable capacitor array **206** includes two n-channel MOSFETs (NMOS transistors) **14**, **16**, two capacitors **18**, **20**, and a number of resistors **22**, **24**, **26**, **28** in electrical connection with each other. Specifically, the gate terminals of the two NMOS transistors **14**, **16** are connected with each other, and with a resistor **22**. The source terminals of the two NMOS transistors **14**, **16** are connected with each other, and with a grounded resistor **24**. The drain terminals of each NMOS transistors **14**, **16** are connected with a grounded resistor **26**, **28** as well as a capacitor **18**, **20**. Preferably, the two capacitors **18**, **20** are electrically connected with the drain terminals of the third and fourth PMOS transistors **210**, **212** respectively. Preferably, the capacitor array circuit **206** has a substantially symmetric circuit architecture. The capacitor array circuit **206** in the present embodiment provides a wide tuning range.

In one embodiment, the second voltage controlled oscillator **200** further includes the resonator tank **208** in the form of a LC resonator circuit. Preferably, the LC resonator circuit **208** includes two branches arranged in parallel between the drain terminals of the third and fourth PMOS transistors **210**, **212**. Preferably, the LC resonator **208** includes two resistors **230**, **232**, two diodes **234**, **236**, two capacitors **238**, **240**, and an inductor **242** in electrical connection with each other. As shown in FIG. 1, in the first branch, there are two diodes **234**,

**236** connected to the same node **244** biased at  $V_{tune}$ . The diodes **234**, **236** are biased in a manner such that current can only flow into but not out of the node **244**. The first branch further includes two capacitors **238**, **240** each connected between a drain terminal of the respective third and fourth PMOS transistors **210**, **212** and a respective diode **234**, **236**. A first sub-branch comprising two resistors **230**, **232** is arranged in parallel with the two diodes **234**, **236**. The resistors **230**, **232** in the sub-branch are connected at the same node **246** at voltage V. In the present example, the voltage V is 0.7 volt. In the present embodiment, the second branch includes an inductor **242** connected to ground, and in parallel with the first branch. Preferably, the LC resonator circuit **208** has a substantially symmetric circuit architecture.

In the present embodiment, the first and second voltage controlled oscillators **100**, **200** are electrically connected with each other through different electrical connections. Firstly, as shown in FIG. 1, the current source **102** of the first voltage controlled oscillator **100** and the current source **202** of the second voltage controlled oscillator **200** are connected with the same node **12** biased at voltage  $V_{dd}$ . Secondly, the first and second voltage controlled oscillators **100**, **200** incorporate a bulk-coupled architecture for connecting the first and second PMOS transistors **110**, **112** and the third and fourth PMOS transistors **210**, **212**.

In the bulk-coupled architecture, the bulk terminals of the PMOS transistors **110**, **112**, **210**, **212** are used to couple the first voltage controlled oscillator **100** with the second voltage controlled oscillator **200**. Referring to FIG. 1, the bulk terminal of the first PMOS transistor **110** is connected with the drain terminal of the fourth PMOS transistor **212** through node  $I^-$ , and the bulk terminal of the second PMOS transistor **112** is connected with the drain terminal of the third PMOS transistor **210** through node  $I^+$ . Also, the bulk terminal of the third PMOS transistor **210** is connected with the drain terminal of the first PMOS transistor **110** through node  $Q^+$ , and the bulk terminal of the fourth PMOS transistor **212** is connected with the drain terminal of the second PMOS transistor **112** through node  $Q^-$ . In the present embodiment, a capacitor **148** is arranged between the bulk terminal of the first PMOS transistor **210** and the drain terminal of the fourth PMOS transistor **212**; a capacitor **150** is arranged between the bulk terminal of the second PMOS transistor **112** and the drain terminal of the third PMOS transistor **210**; a capacitor **248** is arranged between the bulk terminal of the third PMOS transistor **210** and the drain terminal of the first PMOS transistor **110**; and a capacitor **250** is arranged between the bulk terminal of the fourth PMOS transistor **212** and the drain terminal of the second PMOS transistor **112**. These capacitors **148**, **150**, **248**, **250** are operable to perform DC block functions.

A person skilled in the art would understand that variations and modifications based on the preferred configuration of the quadrature voltage controlled oscillator **10** as shown in FIG. 1 are possible. For example, the same current source may be used to provide the current sources **102**, **202** of the first voltage controlled oscillator **100** and the second voltage controlled oscillator **200**. In other embodiments, NMOS transistors may be used in place of PMOS transistors **110**, **112**, **210**, **212**. The quadrature voltage controlled oscillator **10** may be fabricated in other processes other than CMOS.

FIG. 2A shows the simulated time-domain source current and source-gate voltage ( $V_s$ - $V_g$ ) waveforms of the PMOS transistor for the quadrature voltage controlled oscillator of FIG. 1. As shown in FIG. 2A, the voltage at  $Q^+$  and the voltage at  $I^+$  are in quadrature, i.e., 90° out of phase with

each other. Also, under a biasing current of 1.2 mA, a large current pulse (source current) with an amplitude of around 10 mA is generated. With the same power consumption, the oscillator in the present embodiment provides higher oscillation efficiency, which is defined as the ratio of the output power  $P_{RFout}$  to the DC power consumption  $P_{DC}$ :

$$\eta = \frac{P_{RFout}}{P_{DC}} = \frac{P_{RFout}}{V_{DC} - I_{DC}} \quad (1)$$

FIG. 2B shows the simulated oscillation efficiency of the quadrature voltage controlled oscillator of FIG. 1 under different biasing voltages. The Class-AB and the Class-C operation regions are shaded in the Figure.

As shown in FIG. 2B, the oscillation efficiency improves as the biasing condition changes from Class-AB to Class-C. When the PMOS transistors enter Class-C condition (in the present embodiment, when  $V_{bias}=0.75$  V), the narrow-waveform drain current grows rapidly, and this leads to a sharp increase of the oscillation efficiency. In FIG. 2B, the simulated maximum efficiency is around 60%, with 0.677 dBm RF power output, drawing 4.34 mA current from a 1.8 V voltage supply.

The phase noise of the quadrature voltage controlled oscillator in the present invention at an offset frequency of  $\Delta f$  can be derived using

$$L(\Delta f) = 10 \text{Log} \left( \frac{4k_B \cdot T + \gamma_P \cdot k_B \cdot T}{4\pi^2 \cdot \Delta f^2 \cdot C^2 \cdot R_T^3 \cdot I_{c0}^2} \right) \quad (2)$$

where  $k_B$  is the Boltzmann's constant, T is the absolute temperature,  $\gamma_P$  is the proportionality constant,  $R_T$  is the tank resistance, and C is the tank capacitance. Since a higher fundamental current amplitude  $I_{c0}$  has been generated in the oscillator of the present invention that employs Class-C operation, lower phase noise is achieved.

FIG. 2B further shows the variation of simulated phase noise along with the change of biasing voltages. As shown in FIG. 2B, a minimum phase noise of -125 dBc/Hz at 1 MHz offset is realized under Class-C operation. In other words, the Class-C operation in the present embodiment provides more than 5 dB phase noise improvement compared with other working states as shown in FIG. 2B. However, as the biasing voltage is further increased, the oscillation condition is disrupted, and this leads to the phase noise deterioration.

In the present invention, the quadrature generation is realized based on bulk-coupled architecture. Specifically, in the present embodiment, the frequency offset is expressed as

$$\Delta f = f_{osc} - f_0 = \frac{f_0}{2 \cdot Q_{\lambda sik}} \cdot \tan^{-1} \left( \frac{I_C}{I_M} \right) \quad (3)$$

where  $f_{osc}$  and  $f_0$  denote the oscillation frequency of quadrature voltage controlled oscillator and differential voltage controlled oscillator,  $I_C$  and  $I_M$  represent the drain currents of the coupling transistors and the main transistors, respectively. As the bulk-coupled structure of the quadrature voltage controlled oscillator **10** introduces a negligible  $I_C$  current compared with conventional P-QVCO and S-QVCO topologies, the output frequency modulation in the present

invention can be alleviated. As a result, a low phase noise of quadrature signal generation is further assured.

To verify the performance of the quadrature voltage controlled oscillator **10** in the present embodiment of the invention, a quadrature voltage controlled oscillator was designed and fabricated based on the oscillator circuit illustrated in FIG. 1. In the present example, the quadrature voltage controlled oscillator is designed and fabricated in TSMC 0.18  $\mu\text{m}$  CMOS technology. Measurements were performed on the fabricated quadrature voltage controlled oscillator.

FIGS. 3A and 3B show the measured phase noise and tuning curves of the fabricated quadrature voltage controlled oscillator. In FIG. 3A, 1 MHz offset phase noises at the frequency of 5.6 GHz, 6.4 GHz and 6.8 GHz are  $-124$  dBc/Hz,  $-122.3$  dBc/Hz and  $-120.2$  dBc/Hz respectively. In the frequency tuning curves of FIG. 3B, the output power is  $-0.8$  dBm, and the tuning range is 22.6%, covering from 5.58 GHz to 6.94 GHz.

FIG. 3C shows the measured output power at different working frequencies for different bias voltages of the fabricated quadrature voltage controlled oscillator. As shown in FIG. 3C, the achieved maximum output power is  $-0.8$  dBm as the voltage controlled oscillator enters into Class-C condition. In FIG. 3C, the output power varies across the working frequency, and this may be caused by the switching of 4-bit capacitor array.

In order to simultaneously quantify the amplitude and phase error ( $\alpha$ ,  $\phi$ ) of the designed quadrature voltage controlled oscillator, an up-conversion image reject mixer is built and utilized. The image rejection ratio (IRR) of the mixer indicates the amplitude and phase error of the quadrature voltage controlled oscillator, with it is expressed as

$$IRR = \frac{(1 - \alpha)^2 + |2(1 + \alpha) \cdot \cos\phi + 1|}{(1 + \alpha)^2 - 2(1 + \alpha) \cdot \cos\phi + 1} \quad (4)$$

FIG. 4A shows a circuit of the image reject mixer **400** in accordance with one embodiment of the present invention. In the present embodiment, the image reject mixer **400** includes an input filter module **402** arranged to receive an input signal, two mixers **404**, **406** connected with the input filter module **402**, a quadrature voltage controlled oscillator **10** connected with the two mixers **404**, **406**, and an output combiner **408** connected with the two mixers. Preferably, the input filter module **402** is preferably a poly phase filter. The poly phase filter module includes two input channels for receiving an input signal, and four output channels for outputting the processed input signal to the mixers **404**, **406**. Two of the output channels  $I^+$ ,  $I^-$  are connected to a first mixer **404**, whilst two of the other output channels  $Q^+$ ,  $Q^-$  are connected to the second mixer **406**. Preferably, the quadrature voltage controlled oscillator **10** is the same as the one illustrated in FIG. 1. More particular, the bulk terminals of the first and second PMOS transistors in the quadrature voltage controlled oscillator **10** are connected with the first mixer **404**, and the bulk terminals of the third and fourth PMOS transistors in the quadrature voltage controlled oscillator **10** are connected with the second mixer **406**. The quadrature voltage controlled oscillator **10** is arranged to provide a signal to be mixed with the signal outputted from the filter module to the mixers **404**, **406**. The signals processed by the mixers **404**, **406** can then be transmitted to the combiner **408**. The combiner **408** in the present embodi-

ment is arranged to combine these signals and provide a processed output signal through two output channels.

FIG. 4B shows a chip micrograph **450** of the fabricated image reject mixer including a poly phase filter (PPF) and a quadrature voltage controlled oscillator (QVCO) that has the same structure as shown in FIG. 1. In this example, the core area of quadrature voltage controlled oscillator is  $840 \mu\text{m} \times 300 \mu\text{m}$ .

FIGS. 4C and 4D show the measured output power spectrum and the image rejection ratio bandwidth performance of the fabricated mixer, with an input intermediate frequency signal at 70 MHz. As shown in FIG. 4C, a local oscillator (LO) suppression of 50 dB is obtained. On the other hand, as shown in FIG. 4D, the peak value of the measured image rejection ratio is 40 dBc. These results demonstrated that the amplitude and phase errors are within 1% (0.086 dB) and  $1^\circ$ .

For evaluation purpose, the figure of merit (FOM) and  $FOM_T$  are also employed

$$FOM = L(\Delta f) - 20\log_{10}\left(\frac{f_{oc}}{\Delta f}\right) + 10\log_{10}\left(\frac{P_{oc}}{mW}\right) \quad (6)$$

$$FOM_T = L(\Delta f) - 20\log_{10}\left(\frac{f_{oc}}{\Delta f} \cdot \frac{\text{Tuning Range}}{10\%}\right) + 10\log_{10}\left(\frac{P_{oc}}{mW}\right) \quad (6)$$

In the present embodiment, the measured FOM and  $FOM_T$  at 6.4 GHz for the designed quadrature voltage controlled oscillator are  $-189$  and  $-201$  at 1 MHz offset, respectively. Table I shows the performance parameters of the quadrature voltage controlled oscillated in the present embodiment.

TABLE I

Para- meters	Fre- quency	Tuning Range	Phase Noise	Power	FOM	$FOM_T$
Values	6.4 GHz	22.6%	$-122.3$ dBc/Hz	8.64	$-189$	$-201$

The embodiments of the present invention provide a quadrature voltage controlled oscillator that utilizes a PMOS-transistors-only oscillator circuit with a bulk-coupled architecture, and with the transistors and oscillators biased to operate in Class-C mode. In other words, quadrature signal generation in the present invention is realized by the integration of bulk-coupled technique and Class-C operation. Since additional coupling transistors are not used for coupling the two voltage controlled oscillators, no additional noise source is introduced and so phase noise can be improved significantly. In the embodiments of the present invention, the first and second voltage controlled oscillators use PMOS-transistors-only pair as the core transistor. This reduces the thermal and flicker noises, and results in a further improvement of phase noise. By employing Class-C operation, the quadrature voltage controlled oscillator in the present invention can generate high fundamental current using the same power, and this results in a higher oscillation efficiency.

The embodiments of the present invention provides a wideband, low phase noise, wide tuning range, high efficiency quadrature voltage controlled oscillator. The quadrature voltage controlled oscillator in the embodiments of the

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present invention is very suitable for low phase noise, wideband and precise quadrature signal generation.

It will be appreciated by persons skilled in the art that numerous variations and/or modifications may be made to the invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects as illustrative and not restrictive.

Any reference to prior art contained herein is not to be taken as an admission that the information is common general knowledge, unless otherwise indicated.

The invention claimed is:

1. A quadrature voltage controlled oscillator, comprising: a first voltage controlled oscillator having a first current source, a first oscillator circuit, a first tuning circuit, and a first resonator tank electrically connected with each other;
- a second voltage controlled oscillator having a second current source, a second oscillator circuit, a second tuning circuit, and a second resonator tank electrically connected with each other;
- the first oscillator circuit comprises a first transistor, a second transistor and a first biasing circuit connected between the first and second transistors for biasing the first and second transistors to operate in Class-C mode;
- the second oscillator circuit comprises a third transistor, a fourth transistor and a second biasing circuit connected between the third and fourth transistors for biasing the third and fourth transistors to operate in Class-C mode;
- wherein bulk terminals of the first and second transistors are coupled with drain terminals of the third and fourth transistors respectively, and bulk terminals of the third and fourth transistors are coupled with drain terminals of the first and second transistors respectively, such that the first voltage controlled oscillator is electrically coupled with the second voltage controlled oscillator.
2. The quadrature voltage controlled oscillator in accordance with claim 1, wherein the first, second, third and fourth transistors are PMOS transistors.
3. The quadrature voltage controlled oscillator in accordance with claim 1, wherein the first biasing circuit comprises a low pass RC circuit arranged to provide a bias voltage to the first and second transistors to bias the first and second transistors to operate in Class-C mode.
4. The quadrature voltage controlled oscillator in accordance with claim 1, wherein the second biasing circuit comprises a low pass RC circuit arranged to provide a bias voltage to the third and fourth transistors to bias the third and fourth transistors to operate in Class-C mode.
5. The quadrature voltage controlled oscillator in accordance with claim 1, wherein source terminals of the first and second transistors are connected with each other; and source terminals of the third and fourth transistors are connected with each other.
6. The quadrature voltage controlled oscillator in accordance with claim 1, wherein a gate terminal of the first transistor is connected with a drain terminal of the second transistor through the first biasing circuit, and a gate terminal of the second transistor is connected with a drain terminal of the first transistor through the first biasing circuit.
7. The quadrature voltage controlled oscillator in accordance with claim 1, wherein a gate terminal of the third transistor is connected with a drain terminal of the fourth transistor through the second biasing circuit, and a gate terminal of the fourth transistor is connected with a drain terminal of the third transistor through the second biasing circuit.

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8. The quadrature voltage controlled oscillator in accordance with claim 1, wherein the bulk terminal of the first transistor is connected with a drain terminal of the fourth transistor, the bulk terminal of the second transistor is connected with a drain terminal of the third transistor, the bulk terminal of the third transistor is connected with a drain terminal of the first transistor, and the bulk terminal of the fourth transistor is connected with a drain terminal of the second transistor.

9. The quadrature voltage controlled oscillator in accordance with claim 1, wherein the first current source is connected between a node and the source terminals of the first and second transistors for supplying current to the first and second transistors.

10. The quadrature voltage controlled oscillator in accordance with claim 9, further comprising a first capacitor connected in parallel with the first current source between the node and the source terminals of the first and second transistors.

11. The quadrature voltage controlled oscillator in accordance with claim 1, wherein the second current source is connected between a node and the source terminals of the third and fourth transistors for supplying current to the third and fourth transistors.

12. The quadrature voltage controlled oscillator in accordance with claim 11, further comprising a second capacitor connected in parallel with the second current source between the node and the source terminals of the third and fourth transistors.

13. The quadrature voltage controlled oscillator in accordance with claim 1, wherein the first and second current sources are the same current source.

14. The quadrature voltage controlled oscillator in accordance with claim 1, wherein the first tuning circuit comprises a capacitor array.

15. The quadrature voltage controlled oscillator in accordance with claim 14, wherein the first tuning circuit is a 4-bit switchable capacitor array.

16. The quadrature voltage controlled oscillator in accordance with claim 1, wherein the second tuning circuit comprises a capacitor array.

17. The quadrature voltage controlled oscillator in accordance with claim 16, wherein the second tuning circuit is a 4-bit switchable capacitor array.

18. The quadrature voltage controlled oscillator in accordance with claim 1, wherein the first resonator tank comprises an LC resonator circuit.

19. The quadrature voltage controlled oscillator in accordance with claim 1, wherein the second resonator tank comprises an LC resonator circuit.

20. The quadrature voltage controlled oscillator in accordance with claim 1, wherein the first tuning circuit and the first resonator tank are connected across the drain terminals of the first and second transistors.

21. The quadrature voltage controlled oscillator in accordance with claim 1, wherein the second tuning circuit and the second resonator tank are connected across the drain terminals of the third and fourth transistors.

22. The quadrature voltage controlled oscillator in accordance with claim 1, wherein the first voltage controlled oscillator is substantially identical to the second voltage controlled oscillator.

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**23.** The quadrature voltage controlled oscillator in accordance with claim **1**, wherein the quadrature voltage controlled oscillator is a CMOS quadrature voltage controlled oscillator.

**24.** A radiofrequency transceiver comprising the quadrature voltage controlled oscillator in accordance with claim **1**.

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